APPENDIX E. FOAM COVERED WALL PANEL TESTS

E.1 GEOMETRY

The video taken inside the nightclub demonstrated how quickly the foam ignited and how quickly the fire developed. The cellular structure of the polyurethane foam provides a very low density fuel layer that burns quickly. A series of wall burns were conducted to provide insight into how the geometry impacted the growth and spread of the fire. These data assisted in the design of the mockup experiments and provided guidance for the simulation of the entire nightclub.

Ignition of the foam on the wall of the nightclub by the gerbs occurred at the edge of an exterior corner of the drummers alcove, as described in Chapter 4. During the first 15 seconds of the fire, flames spread quickly upward and less quickly downward and laterally. To simulate this arrangement, two 0.064 m (0.25 in) thick plywood backer board panels, each 1.22 m (4 ft) x 2.44 m (8 ft), were mounted perpendicular to each other to form an external corner as shown in Figure E-1. The panels were supported on 2 x 4 studs and covered with a full sheet of non-fire retardant polyurethane foam (1.22 m x 2.44 m x 0.025 m) from lot A. The plywood was screwed to the studs and the foam was mounted to the plywood using staples and adhesive.

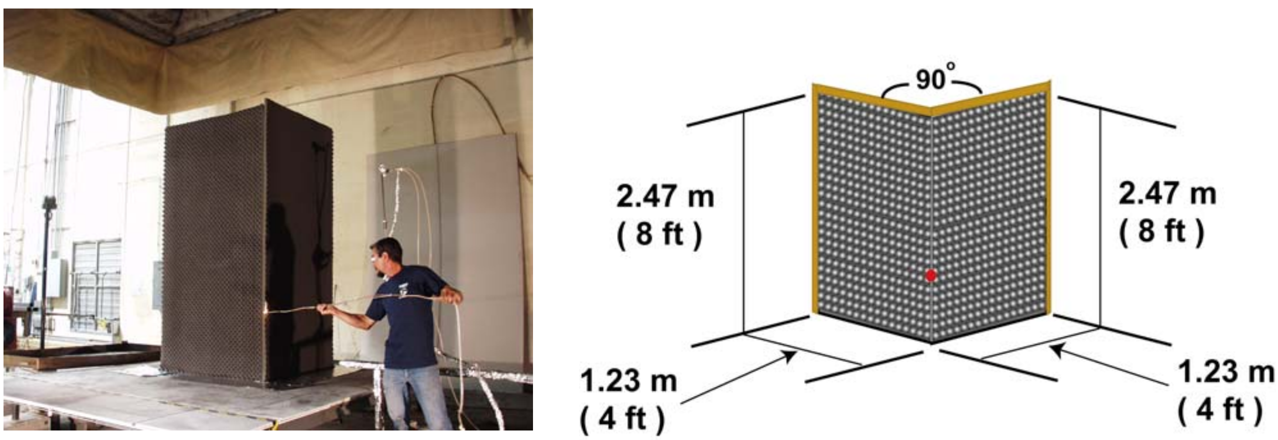


Figure E-1. Photograph and Dimensioned Diagram of External Corner

A second experiment used the identical 1.22 m (4 ft) x 2.44 m (8 ft) panels (0.025 m thick non-fire retarded lot A polyurethane foam on 0.064 m (0.25 in) thick plywood backer board, supported on 2 x 4 studs), but arranged to simulate an internal corner. (See Figure E-2.) An internal corner leads to faster flame spread than an external corner since in the former arrangement each surface is exposed to radiant heating from the adjacent wall. In both the mock-up and the actual nightclub fire, flame spread was enhanced further by the presence of the hot layer that built up at the ceiling. The corner arrangements examined here were open to the environment at the top (no ceiling); hence, the flame spread did not continue to accelerate.

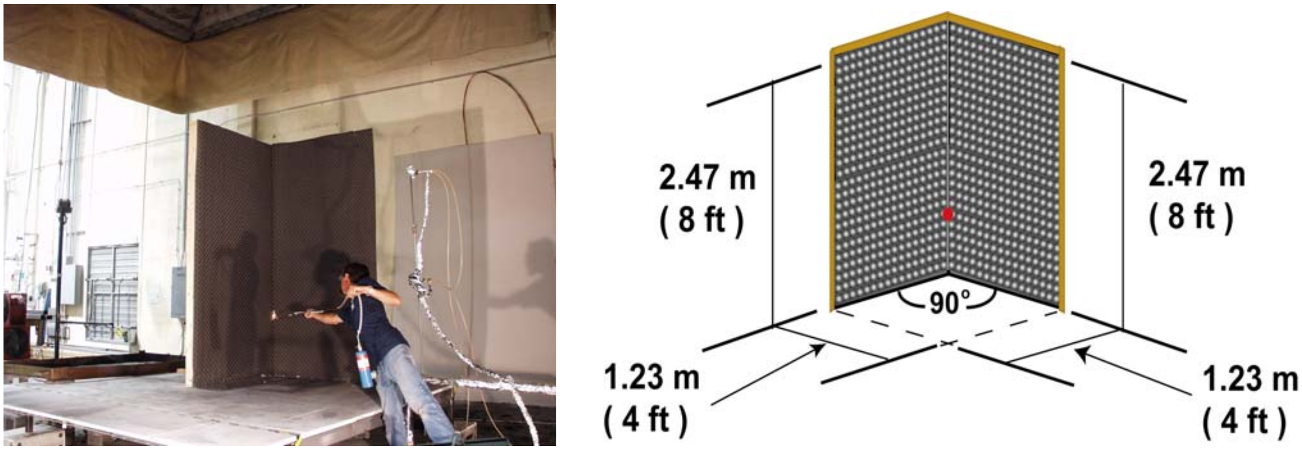


Figure E-2. Photograph and Dimensioned Diagram of Internal Corner

A propane torch was used to ignite the corner of the foam at 0.61 m (24 in) above the floor. While this was lower than the point of ignition in the nightclub, the purpose of these experiments was not to duplicate the fire growth, but to provide a controlled environment in which flame spread measurements (upward, downward, and lateral) could be accurately determined. The fire was videotaped from two directions, and the radiant heat flux and total heat release rate were measured. Figure E-3 includes a video of the external corner burn and internal corner burn, side by side, with a clock.

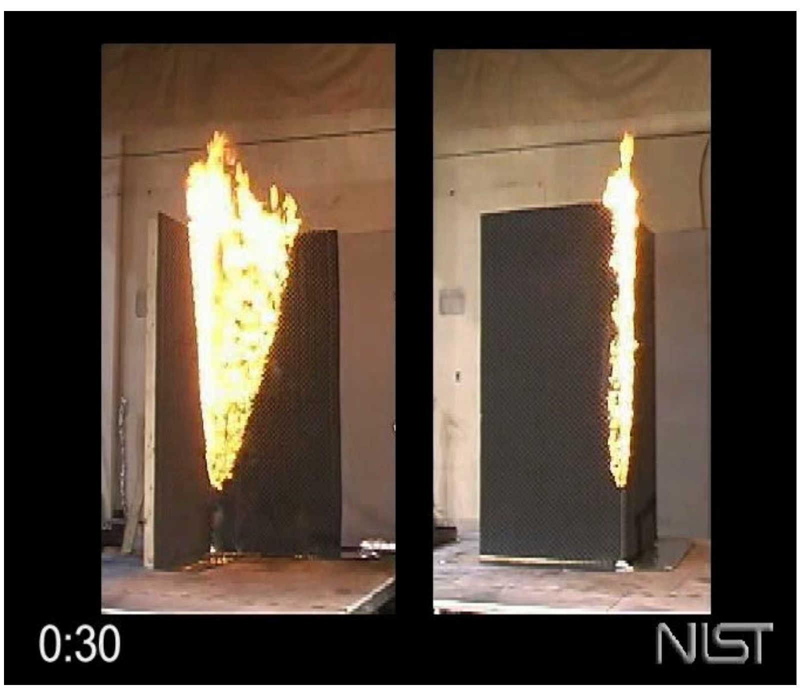


Figure E-3. Video of External and Internal Corner Burns

E.2 DESCRIPTION OF THE FIRES AND HEAT RELEASE RATES

E.2.1 External Corner Configuration

Figures E-3 (right video) and E-5 show the progression of fire in the external corner configuration for the first 610 seconds of the test. The flame spread can be broken into four distinct phases. In the first phase, the fire spreads upward rapidly, with flames reaching the top of the panel before they have had much chance to spread downward or laterally. Once the flames have reached the top of the panel, lateral spread occurs in the second phase, resulting in a vee-shaped flame with the vertex at the corner slightly below the point of ignition. The polyurethane melts and flows down the corner in the third phase, rapidly causing the flame to extend to the ground and to create a small pool fire. In the fourth phase, the flame extends from the floor to the upper edge of the panel, forming a line fire which spread laterally along the bottom and top edges. The flame on the upper horizontal edge reaches the vertical extent of the panel first, at which time the fire spreads downward until all of the foam is consumed. By the end of the test, the plywood backing can be seen to be burning near the initial point of ignition.

Since the wall panels were burned under an instrumented calorimetry hood, it was possible to utilize oxygen depletion measurements to calculate the heat release rate. The results for the external corner are plotted as the blue line in Fig. E-4. The heat release rate reached a peak value of 200 kW between 160 and 180 seconds after ignition. From the photos in Fig. E-3 taken 120 and 180 seconds into the burn, one can attribute this peak to the pool fire enhanced burning during the third phase of flame spread. The heat release rate included the energy released by all the fuel. Initially, the burning of the foam contributed most of the energy released by the fire while the wood contributed more energy as the foam was consumed. During phase 4, the heat release rate gradually reduces to about half its maximum value until

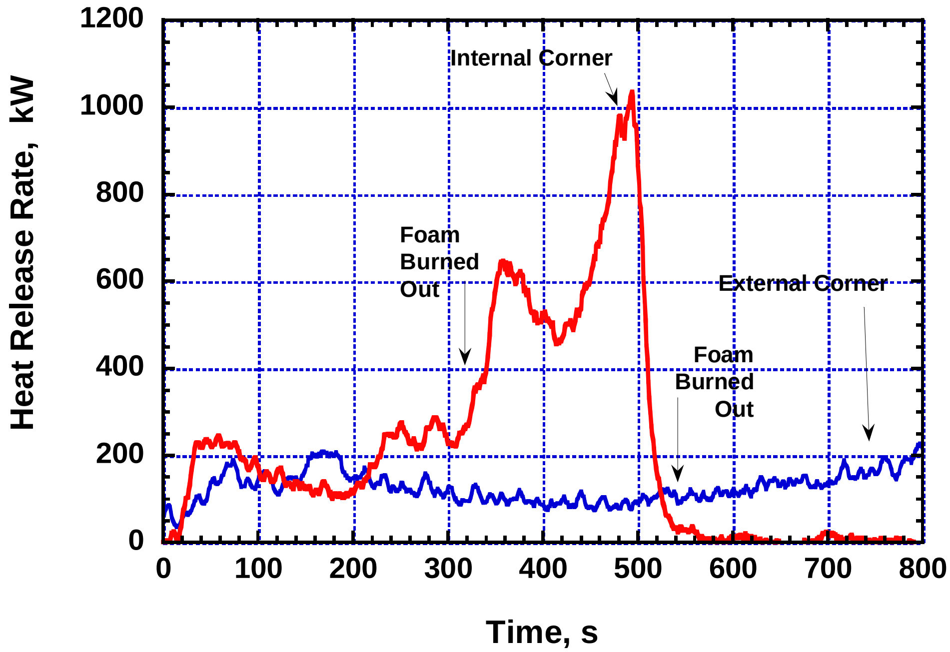
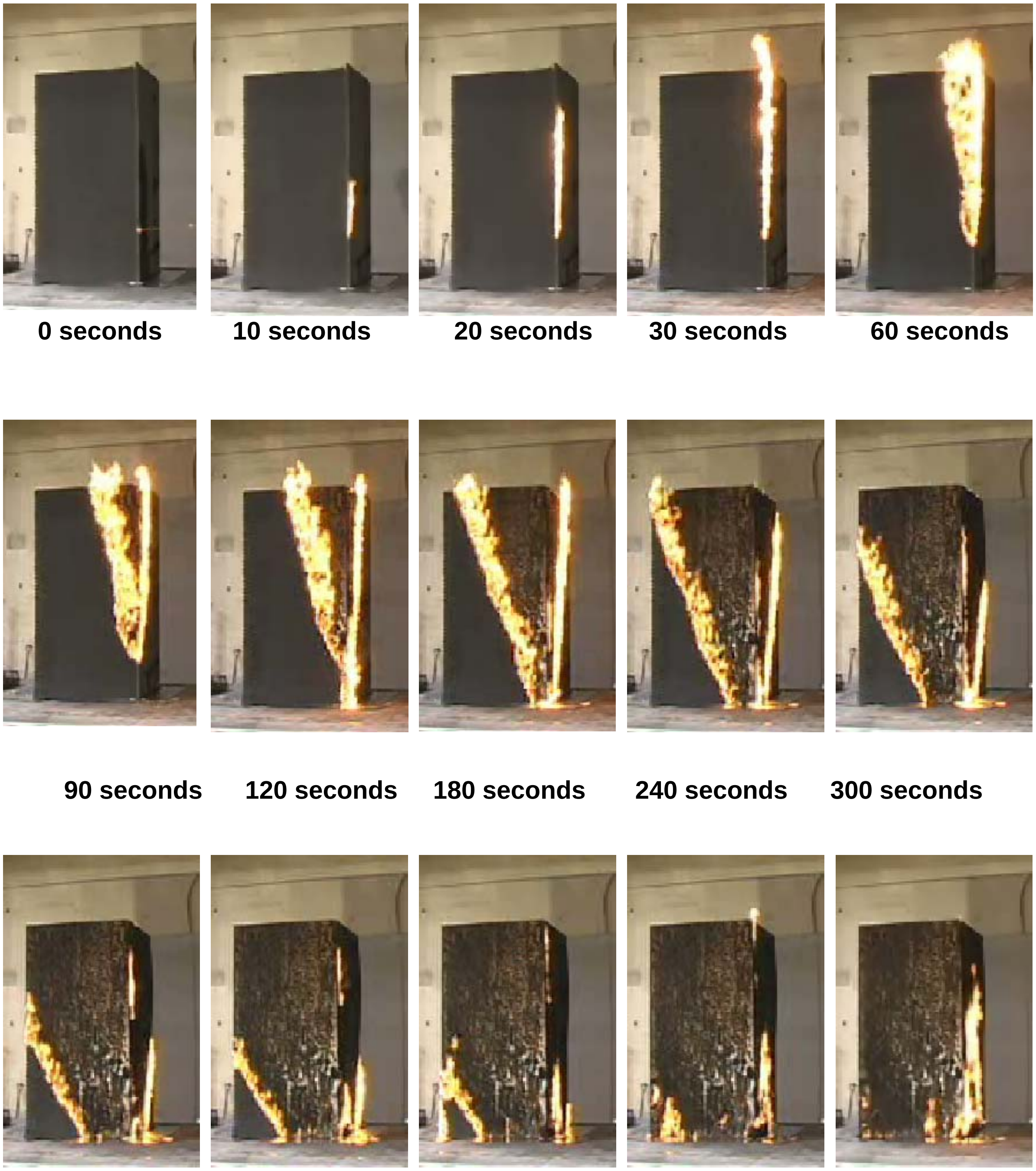


Figure E-4. Heat release rate versus time for external and internal corner configurations of foam covered wall panels.



0 seconds, 10 seconds, 20 seconds, 30 seconds, 60 seconds

90 seconds, 120 seconds, 180 seconds, 240 seconds, 300 seconds

360 seconds, 420 seconds, 480 seconds, 540 seconds, 610 seconds

Figure E-5. Flame spread over polyurethane foam covered panels, external corner configuration.

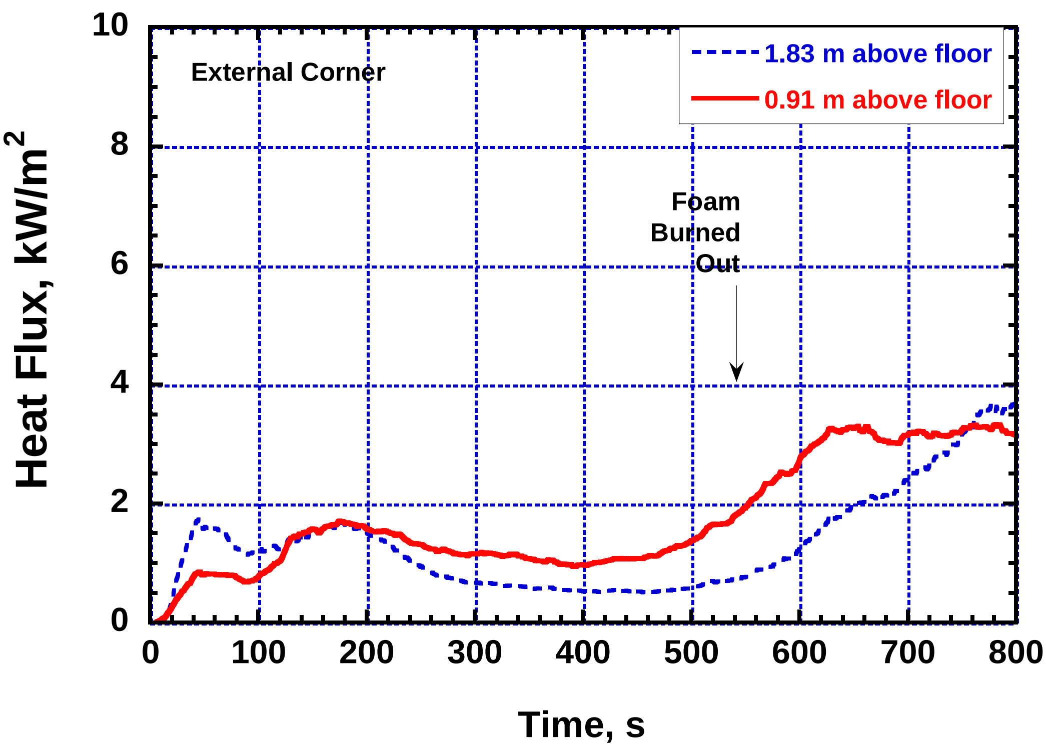


Figure E-6. Heat flux versus time for external corner burn.

almost all of the foam has been consumed at 540 seconds. The increase in heat release rate seen in Fig. E-4 after this point in time is due to the burning of the plywood panel. The irradiation perpendicular to and 2 m from the burning surface mirrors the heat release rate, as shown in Fig. E-6, attaining a value slightly above and below 1 kW/m^2 from measurements 0.91 m and 1.83 m, respectively, above the bottom of the panel.

The total energy contributed by the foam to the fire can be estimated from the area under the blue curve in Fig. E-4 to be 60 MJ to 70 MJ. This compares to any energy content of about 95 MJ for two 1.22 m x 2.44 m x 0.025 m thick panels of foam, using a heat release per unit area of 15.8 MJ/m^2 as measured in the cone calorimeter with an incident flux of 35 kW/m^2. The difference in total energy may be attributable to residual foam on the panel, liquid fuel that remained unburned on the floor, or less complete combustion of the panels as compared to the cone calorimeter sample irradiated at 35 kW/m^2.

E.2.2 Internal Corner Configuration

The internal corner test was conducted in the same manner as the test described above. Figure E-8 captures the fire during the first 400 seconds of the test. The same four phases of fire growth can be seen in Fig. E-5, however the rate of growth is considerably faster than occurred in the external corner configuration (compare left and right videos in Fig. E-3), as would be expected due to the enhanced feedback from the adjacent panel. The third phase, in which the melting foam forms a pool at the corner and rapidly drives the downward spread to the floor, occurs around 40 seconds into the internal corner test, as compared to some time around 120 seconds in the external corner test. The pool fire continues to burn and grow while the line fire associated with the fourth phase is established. By 400 seconds, the plywood backing is fully involved. A careful inspection of Fig. E-5 reveals what appears to be a continuously burning melt pool along the bottom edge of the panels as late as 400 seconds into the test.

The heat release rate from the internal corner test is plotted as the red line in Fig. E-4. The irradiation measured perpendicular to and 2 m away from the panel is plotted in Fig. E-7. The shapes of the first 200 seconds for both plots are similar to what was found during the first 500 seconds of the external corner test, although the magnitudes are larger for the internal corner fire; that is, a peak heat release rate in excess of 200 kW, corresponding to the phase 3 burning, occurs early, followed by a gradual decrease to about half the peak heat release rate, and the heat flux from the surface during this period is a bit over 1 kW/m^2 . The Beyond 200 seconds, the internal corner test undergoes a more complicated behavior, as the pool fire at the base of the panel grows. The vertical arrow at 310 seconds marks the time when no more foam was visible on the wall panels. The pool fire from the melted foam reached a maximum heat release rate of 650 kW about 360 seconds into the burn. The increase in the fire size after 420 seconds is caused by the burning plywood along the vertical corner. The fire was extinguished at 490 seconds. [Note that while the shape of the flame seen in Fig. E-8 at 400 seconds is reminiscent of the M-shaped pyrolysis region reported by Qian et al.[1], inspection of the panels following their extinguishment revealed that the dark region seen in the photo along the vertical corner was due to complete burnout of the thin plywood panel.]

The total energy released by the fire can be estimated by integrating the area under the red curve in Fig. E-4. There is a substantial uncertainty in how much of the power to attribute to the foam and how much to the wood for times longer than 300 seconds. If one assumes that that the measured heat release rate between 310 and 410 seconds is due primarily to the liquid fuel at the base of the wood panels, then the total energy released by the foam would be about 106 MJ, which is greater than the 95 MJ of energy

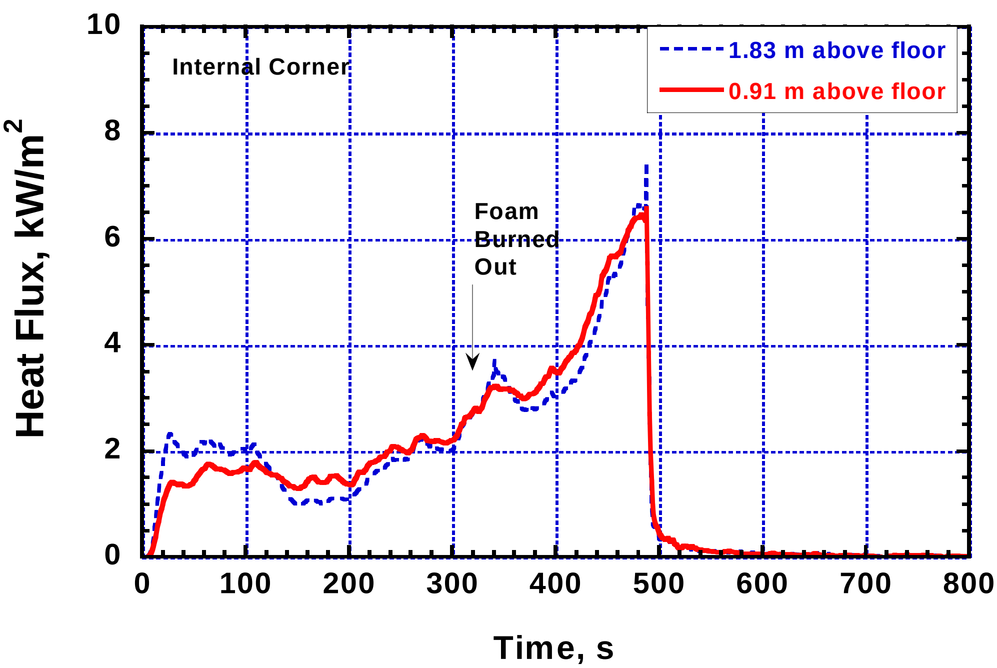
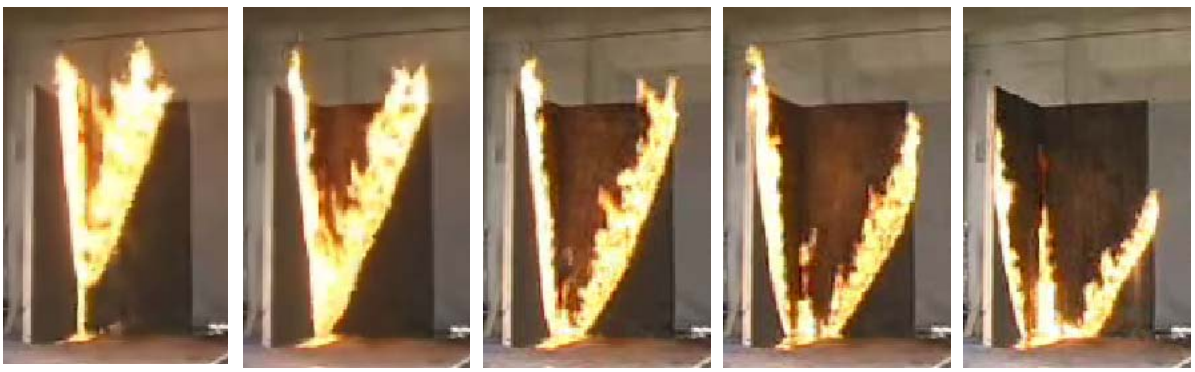


Figure E-7. Heat flux versus time for external corner burn.

0 seconds 5 seconds 10 seconds 20 seconds 30 seconds



40 seconds 60 seconds 90 seconds 120 seconds 150 seconds

180 seconds 240 seconds 290 seconds 350 seconds 400 seconds

Figure E-8. Flame spread over polyurethane foam covered panels, internal corner configuration.

estimated to be in the two foam panels. The burning wood accounts for much of this discrepancy, although it is also likely that the internal corner would produce more complete combustion than the external corner due to the enhanced radiant interchange between the two adjacent panels.

E.3 FLAME SPREAD RATES

E3.1 External Corner Configuration

The speed at which the flames travel across the foam surface during each of the four phases of the fire can be estimated from the video record. While it is not possible to see through the flame to the pyrolysis zone during the first phase, when upward flame spread is dominant, the brightest portion of the flame can be used as a marker of the pyrolysis zone to roughly estimate the upward flame spread rate. The position of the leading edge of the flame in countercurrent regions provides a more accurate measure of the movement of the bulk of the pyrolysis zone as long as the time required to burn through the thickness of the foam is much less than the time for the flame to move across the surface. This is a reasonable assumption for a relatively thin sheet of low density, highly porous material like polyurethane foam, and is confirmed by inspection of the burned out regions behind the countercurrent flames.

Figure E-9 is a plot of the position of the flame along the boundaries of the panel as a function of time, showing the upward, downward (initially on the right of the panel, and later along the left edge), and lateral flame spread (along the top and bottom, respectively) as a function of time and position. The dotted lines in the figure are drawn to represent the approximately steady region of flame spread, and their

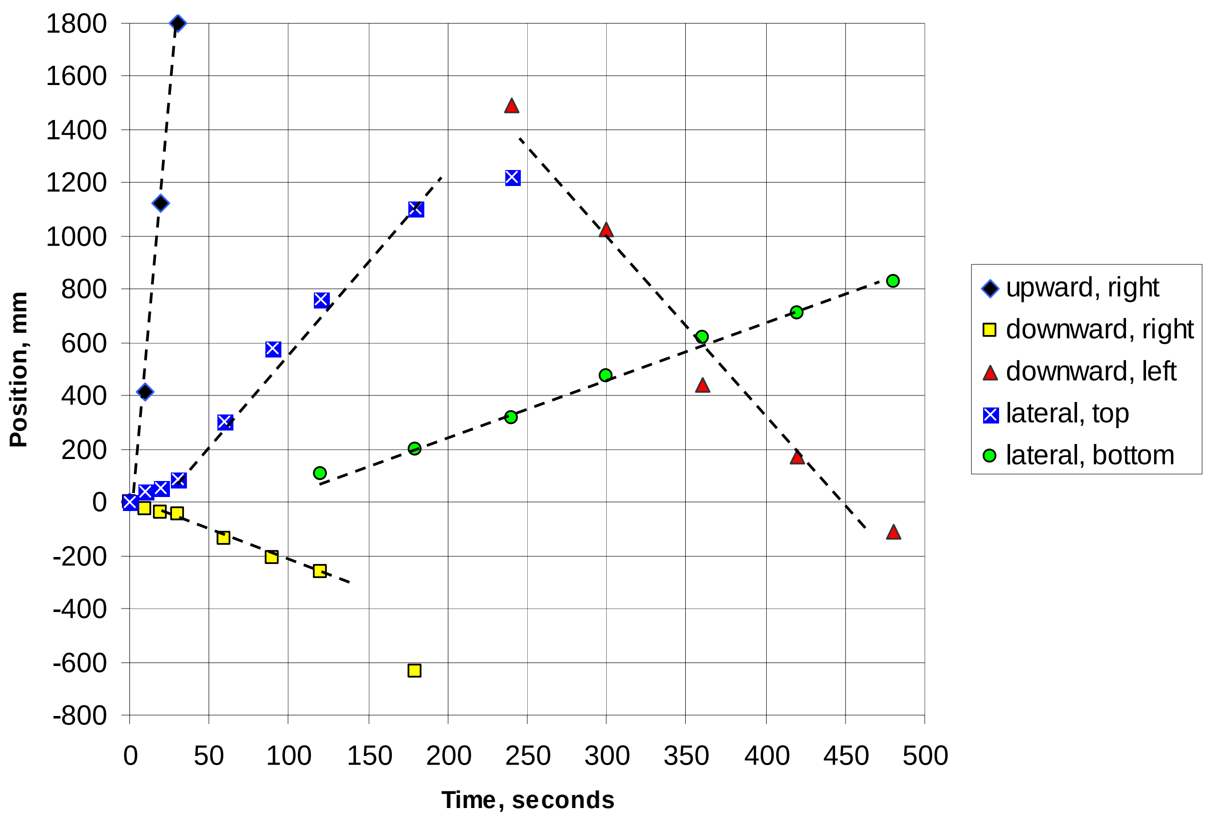


Figure E9. Flame position relative to ignition point on external corner configuration

Table E-1. Approximate flame spread rates over flexible polyurethane foam panels configured as vertical corners

Burning Phase	Direction of Spread	External Corner	Internal Corner
I	Upward (co-current)	63 mm/s	135 mm/s
II	Downward (counter-current)	2.3 mm/s	6.4 mm/s
II - IV	Lateral, top (counter-current)	6.8 mm/s	24 mm/s
IV	Lateral, bottom (counter-current)	2.2 mm/s	4.4 mm/s
IV	Downward (counter-current)	7.0 mm/s	14 mm/s
II, IV	Normal (counter-current)	7.2 - 7.3 mm/s	15 - 25 mm/s

slopes correspond to the respective spread rates. Table E-1 provides a summary of the estimated spread rates for the external corner configuration. The last row is the normal flame speed (the vector sum of the horizontal and vertical components) during the later phases of burning. The flame speed decreases from a maximum of 63 mm/s in the upward direction to just over 2 mm/s in the downward and lateral direction along the bottom edge of the panel. The normal flames speed during the steady burning period is 7.2 to 7.3 mm/s.

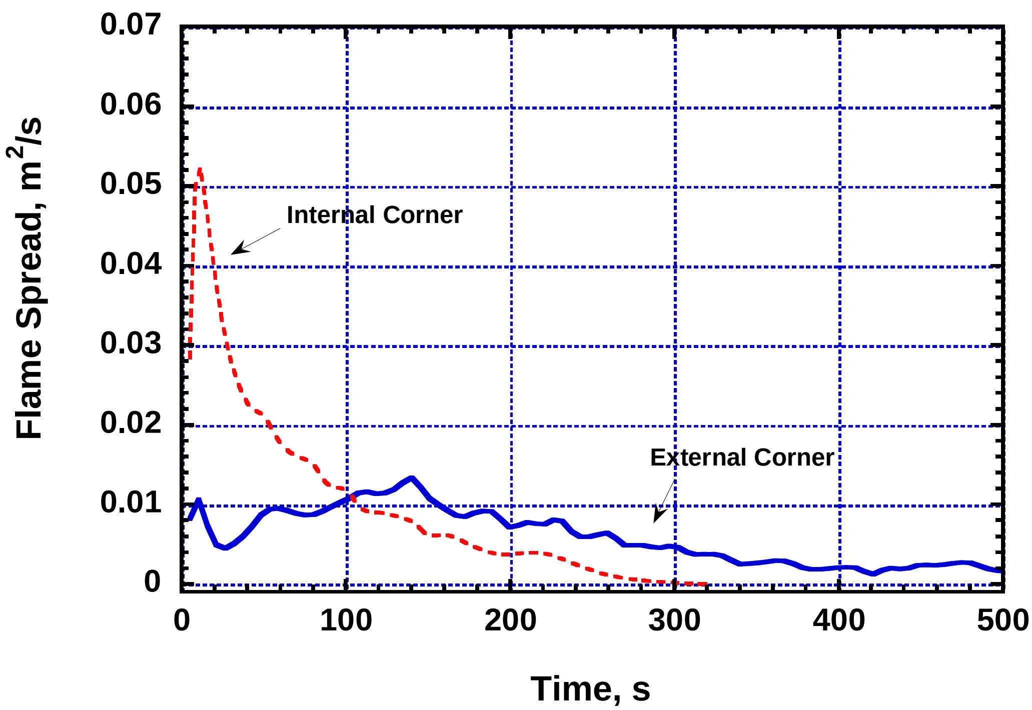


Figure E-10. Flame spread across foam covered wall panel (m^2/s).

The video images were processed to track the unburned portion of the panel not covered by flames to provide an estimate of the surface area burning rate. The result is shown as the blue line in Fig. E-10. Following a small spurt during the initial rapid upward flame spread, the area burning rate drops and then slowly increases in the second and third phases to reach a peak of 0.013 m^2/s about 140 seconds into the fire. The area burning rate gradually declines over the phase 4 period as the line of fire shortens about linearly with time. From the estimated downward and lateral flame speeds listed in Table E-1 and assuming the shape of the unburned foam remains approximately congruent to a triangle formed by the edges and diagonal of the panel, the area burning rate can be expressed as $(X_0 v_y + Y_0 v_x)/2 - v_x v_y (t - t_0)$, where X_0 and Y_0 are the lengths of the sides of the panel, v_x and v_y are the components of the normal flame velocity, and t_0 is the time when the flame begins moving downward along the outer edge of the panel. Using this formulation the area burning rate diminishes from 0.0070 m^2/s at 200 seconds to 0.0024 m^2/s at 500 seconds, consistent with the more accurate calculation represented by Fig. E-10.

E.3.2 Internal Corner

A similar analysis was conducted for the flame spreading over the polyurethane foam panels in the internal corner configuration. Figure E-11 shows the position of the flame, relative to the initial ignition point, as a function time. The same flame spread regions can be identified as with the external corner test. The time axis in Fig. E-11 has been expanded by a factor of two over Fig. E-9, indicative of the faster flame spread associated with the internal corner.

The last column in Table E-1 lists the flame spread rates, taken from the slopes of the curves in Fig. E-11, for different directions throughout the duration of the test. The table entries are two to three times faster than for the external corner, with the biggest difference being the lateral spread across the top of the panels (compare 24 mm/s to 6.8 mm/s). This is the region which is exposed to the largest flames and the highest view factor to enhance the surface irradiation.

The red line in Fig. E-10 is a plot of the area burning rate determine by processing the video images such as those seen in Fig. E-3 and E-8. The initial peak exceeds 0.05 m^2/s, which undoubtedly is an over estimate since the quickly growing flames conceal a portion of the foam panel that has not had time to be completely consumed. Applying the same formulation $[(X_0 v_y + Y_0 v_x)/2 - v_x v_y (t - t_0)]$ developed in section E.3.1 for the area burning rate, a lateral flame speed of 4.4 m/s, and a downward flame speed of 14 mm/s, the flame spread can be estimated to decrease from 0.014 m^2/s at 90 seconds to 0.001 m^2/s at 300 seconds, again consistent with Fig. E-10.

E.4 COMPARISON OF RESULTS TO MOCK-UP AND OTHER STUDIES

E.4.1 Fire Spread in Platform Area Mock-up Experiment

The geometry of the foam panels used in the full-scale mock-up of the drummer's alcove and the area around the platform was considerably more complex than the simple corners used in the flame spread experiments described above. The most significant complication comes from the ceiling, which produces horizontal edges and three-dimensional corners that affect the heat feedback and the flame spread mechanisms. The second significant effect of the ceiling is that it traps the combustion products and heat, leading to a vitiated environment and a rapidly increasing source of thermal radiation, either of which can greatly alter the flame spread rate.

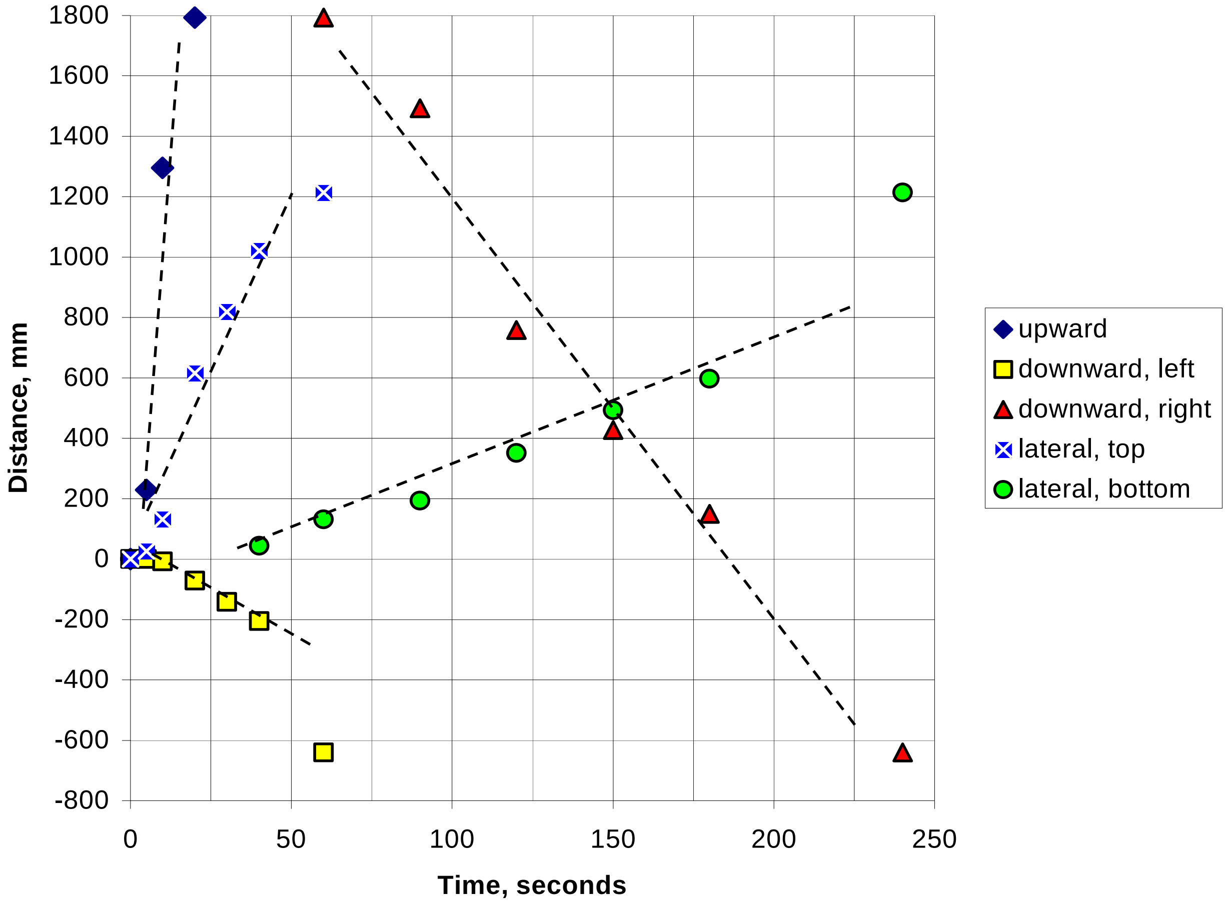


Figure E-11. Flame position relative to ignition point on internal corner configuration

If the video of the fire spread across the face of the east wall along the back of the platform is analyzed in the same manner as the fire spread across the corner panels, the following estimates of flame spread can be achieved:

- upward spread rate (0-10 seconds): 60 mm/s to 100 mm/s
- downward spread rate (0-20 seconds): 4 mm/s to 5 mm/s
- lateral spread rate (10 - 25 seconds): 11 mm/s to 26 mm/s

The lateral spread rate was computed from the increase in the full width of the fire plume, and then reduced by a factor of two to make it comparable to the flame spread in one direction from the corner panel experiments. The lateral flame speed was also determined by tracking the time it took for the thermal wave to reach thermocouples mounted in the foam 300 mm below the ceiling ,every 300 mm along the back wall. Fifteen seconds after ignition, the lateral flame spread rate was 11 mm/s; by 45 seconds after ignition the lateral spread rate had increased to 18 mm/s, in agreement with the video record.

One would expect the flame spread during the initial portion of the fire to be closer to the external corner panel experiments; however, the results for the mock-up in the upward, downward, and lateral flame spread rates lie between those measured in the internal and external corners. It should be noted that the non-fire retarded polyurethane foam used in the mock-up was from lot B, while the foam used in the corner panel experiments was from lot A. While the mass per unit area of the lot A foam was 50 % greater than the lot B foam, cone calorimeter measurements of the peak heat release rates and times to ignition with an irradiation of 35 kW/m^2 were within 5 % of each other.

Dripping of the melted foam along the external corners of the alcove occurred about 25 seconds after ignition. Because the initial point of ignition was much higher in the mock-up than in the corner panel experiments, phase II burning that became prevalent in the latter did not play a roll in the spreading the fire to the floor of the platform.

The lateral flame spread in the northerly direction along the east wall at the back of the platform stalled around 30 seconds after ignition. This appeared to be due to the high rate of air being entrained into the vigorously burning alcove, and the resulting high air velocity running counter to the flame along the back wall. Because the mass loading was less with the lot B foam, the stalled flame allowed the fuel to be consumed without spreading. Thus, the lateral spread mechanism observed in the panel tests did not contribute much to the fire development along the back wall of the platform in the mock-up for more than 30 seconds into the test.

Between 40 seconds and 60 seconds after ignition, most of the action occurred in the alcove, where the heat was transferred effectively to the foam due to intense radiation and high gas temperatures. The hot upper layer developed quickly between 60 seconds and 75 seconds, reaching close to 600 ^{o}C almost everywhere throughout the room. Radiant heat fluxes were measured in excess of 40 kW/m^2 during this period, much higher than imposed by the spreading flame in the corner panel experiments, and above the flux necessary for ignition within a few seconds.

E.4.2 Comparison to Previous Flame Spread Studies

Flame spread is a classic problem for fire science that has been investigated for decades, both theoretically and experimentally. The orientation of the fuel, the direction of the flame spread relative to the air flow, the geometry and properties of the fuel, and the temperature and composition of the environment all play a significant role. For the present discussion, we are interested primarily in counter-current flame spread over vertical walls, with fuels similar to polyurethane.

Quinterre and Harkleroad [2] focused on a method for measuring lateral flame spread over a wide variety of materials. They examined several foams, designated as (1) polyurethane S353M, (2) 25 mm flexible foam, and (3) 25 mm rigid foam. Lateral spread rates of the rigid foam, measured in the LIFT apparatus [4], increased from under 2 mm/s with irradiance levels below 10 kW/m^2 to over 10 mm/s with irradiance levels around 15 kW/m^2. The minimum heat flux necessary for unpiloted ignition was 20 kW/m^2. At this flux level the ignition delay time was around 5 seconds, dropping to about a second at 30 kW/m^2. The 25 mm flexible foam had a much greater lateral spread rate, exceeding a value of 25 mm/s for incident fluxes less than 10 kW/m^2. There is no indication in the report of chemical composition or either the rigid or flexible foams. The one material specifically identified as polyurethane (S353M) was not identified as either rigid or flexible, although it behaved more like the undesignated flexible foam.

Cleary and Quintiere [3] performed additional experiments on foam plastics using several different flammability test methods. For one non-fire retarded polyurethane foam tested in the LIFT apparatus, they measured a maximum flame spread rate of over 40 mm/s with an incident flux of about 10 kW/m^2, the highest flame spread rate at that flux level of all the materials evaluated.

In both of the above studies, the flame spread velocity (v_L) is assumed to be inversely proportional to the product of the effective thermal conductivity (k), density (ρ) and specific heat (c) of the foam according to the relationship [2]

$$v_L = \Phi\, h^2/(k\rho c)\,/(q''_{ig} - q''_e)^2$$

where h is the heat transfer coefficient to the surface, q_{ig} is the heat flux necessary to ignite the material in a finite period of time, q''_e is the imposed heat flux, and Φ is a flame heating parameter.

An effective value is used for (kρc) because the properties change with temperature and the extent of pyrolysis. The ignition delay time measured in the cone calorimeter, t_{ig}, can be used to estimate (kρc) from the following relationship [2]:

$$k\rho c = 4/\pi\, [q''_e/(T_{ig} - T_s)]^2\, t_{ig}$$

where ($T_{ig} - T_s$) is the difference between the ignition temperature and the initial surface temperature of the material. For the PUF-NFR-B, at 35 kW/m^2 the time to sustained ignition was 6 seconds. Using an ignition temperature of 370 ^oC as measured by Southwest Research Institute for this foam, kρc is calculated to be 0.075 $(kW/m^2\text{-}^oC)^2$-s. This compares to 0.001 $(kW/m^2\text{-}^oC)^2$-s computed from the reference values in Table 4.1, and to 0.036 $(kW/m^2\text{-}^oC)^2$-s as tabulated by Cleary and Quintiere [3] for their non-fire retarded polyurethane foam. For this same foam they found Φ to be equal to 3.1 kW^2/m^3 and q''_{ig} to be 14.5 kW/m^2; for other polyurethanes Φ may be twice as high. With these values, and a natural convections coefficient taken as 0.015 $kW/m^2\text{-}^oC$, the lateral flame speed (mm/s) can be related to the irradiation (kW/m^2) by $v_L = 124/(14.5 - q''_e)^2$. To the extent this relationship approximately holds for the PUF-NFR-A material studied in the corner panel configuration, to achieve the lateral spread rate observed in the external corner test (6.8 mm/s) would require a radiant flux from the flame to the surface of about 10 kW/m^2. The internal corner test produced a lateral spread rate of 24 mm/s, corresponding to 33 kW/m^2. If a value for Φ were increased to 6 kW^2/m^3, the required heat flux from the flame to sustain a 24 mm/s lateral flame spread would decrease to 24 kW/m^2.

E.5 REFERENCES FOR APPENDIX E

[1] Qian, C., Ishida, H., and Saito, K., "Upward Flame Spread along PMMA Vertical Corner Walls Part II: Mechanism of "M" Shape Pyrolysis Front Formation," *Combustion and Flame 99:* 331-338 (1994).

[2] Quintiere, J., and Harkleroad, M., "New Concepts for Measuring Flame Spread Properties," NBSIR 84-2943, National Bureau of Standards, November 1984.

[3] Cleary, T., and Quintiere, J., "Flammability Characterization of Foam Plastics," NISTIR 4664, National Institute of Standards and Technology, October 1991.

[4] ASTM E 1321-97a, *Standard Test Method for Determining Material Ignition and Flame Spread Properties*, ASTM International, West Conshohocken, PA, 2004.